Summary of current agreement among PMD measurement techniques

P.A. Williams, *National Institute of Standards and Technology, Boulder CO, USA*
A.J. Barlow, *EG&G Fiber Optics, Wokingham, UK*

If the average polarization mode dispersion (PMD) of a highly mode coupled fiber is measured by two different techniques, will the results agree? Recently, much work has been done in order to answer this critical question. In this document, we summarize the theoretical and experimental agreement between the four common PMD measurement techniques: Jones Matrix Eigenanalysis (JME), Fixed Analyzer with Extremum Counting (FAEC), Fixed Analyzer with Fourier Transform analysis (FAFT) and low coherence interferometry (INT).

I. Theoretical Predictions:

In our comparison, we use the following definitions [1-3]:

JME:	Avg DGD ≡ <DGD>
	RMS DGD ≡ $<DGD^2>^{1/2}$.
FAEC:	PMD_{EC} ≡ Average PMD.
INT and FAFT:	PMD_{INT}≡ Square root of second moment of interferogram.

In order to describe the theoretical agreement between measurement methods, one important statistical concept must be understood. PMD represents the expected value of the dispersion resulting from the polarization dependence of group delay in the fiber. This expected value is to be distinguished from an instantaneous value. In order to obtain the expected value, PMD is usually measured by averaging the polarization dependent delay over a range of wavelengths. However, the spectral width of typical sources is insufficient to provide an average PMD of high enough precision for useful comparison. So, a second method of averaging is often employed – time averaging. Time averaging means measuring the test fiber once, then perturbing the mode coupling geometry of the fiber (either by physical manipulation of the fiber or temperature change, or merely allowing it to settle with time) and then the PMD is measured again. If these multiple measurements are truly statistically independent, then the average value of *n* such measurements will converge toward the true statistical mean with a standard deviation of the mean that goes like $1/\sqrt{n}$. This means that single measurements of a fiber using two different techniques are not expected to agree. It is only the average of multiple statistically independent measurements that will have agreement between methods.

With this in mind, the following is a summary of the current theoretical results describing the expected agreement between measurement techniques.

Avg DGD = RMS DGD / 1.085 [4]

Avg DGD = PMD_{EC} [4].

$PMD_{INT} = PMD_{FT}$ [5]

RMS DGD($\Delta\tau\Delta\omega$>256) = $0.866 \cdot PMD_{INT}$ [6]
RMS DGD($\Delta\tau\Delta\omega$<256) = $(0.866 \text{ to } 0.98) \cdot PMD_{INT}$ [6]

The relationship between RMS DGD and PMD_{INT} depends on the product of the fiber PMD $\Delta\tau$ and the source bandwidth $\Delta\omega$. For large values, RMS DGD and PMD_{INT} are related by the factor 0.866. For small values of the PMD-bandwidth product, the agreement is somewhat ambiguous because it depends on the exact spectral shape of the source, but the agreement will generally be between 0.866 and 0.98.

The fact that there is a non-unity factor relating frequency domain measurements (JME) to time domain measurements (INT or equivalently FAFT) does not mean that one of the methods is not measuring the right answer. Instead, this factor simply illustrates that JME and INT (FAFT) methods were developed independently with slightly different definitions of PMD. The 0.866 factor can be thought of as similar to the k factor used in the FAEC technique. The k factor is less controversial because it is a part of the PMD_{EC} definition. In contrast, the 0.866 factor was not discovered until after widespread use of the INT and FAFT techniques, and so has not been adopted into the definition of PMD_{INT} or PMD_{FT}.

II. Experimental verification

The major impediment to the experimental verification of the above theoretical predictions is the large number of independent measurements required to obtain sufficiently small uncertainty. Although experimental comparisons have been undertaken several times, most of the experimental data sets are of insufficient size. In order to expand on those works, we here combine the available data sets in order to obtain a larger statistical base from which to draw conclusions regarding the agreement between measurement techniques. The data used in this summary comes mostly from published sources [7-15], but also includes some unpublished data as well. The data is from 11 sources representing 7 participants yielding 563 data points from measurements on many different fibers.

We summarize the data in Figures 1-3 illustrating the measured agreement between the four techniques. The figures illustrate several things. First, as expected, the data at low values of DGD have a significantly larger spread than those at high values. This is attributable to the inherent statistical uncertainty of PMD measurements [4, 16].

In calculating the "average agreement" or the average ratio of two particular measurements, some care must be taken. The goal is to find the ratio to be expected when competent measurements are made. We realize that the collections of data we used are from many different participants with different analysis techniques. So, we need an averaging technique that allows each participant or analysis technique a more or less equal say. A simple average where the sum of the total data set is divided by the number of points would be inadequate since participants who measured many points would have their technique's result weighting the ratio more strongly than the others. We summarize the data using the method of moment averaging technique which weights the data based on both the number of points in and the standard deviation of each data set [18]. The results are shown below.

	Weighted average	**95% Confidence**
Avg DGD / PMD_{EC}	*0.97*	*± 0.09*
RMS DGD / PMD_{FT}	*1.00*	*± 0.09*
RMS DGD / PMD_{INT}	*1.03*	*± 0.07*

The interpretation of these results must be approached with some cautions. First, this data is only a compilation of measurements from several sources. The exact analysis methods of each data set are not fully known. Keep in mind that these numbers represent the typical agreement which may be expected between measurement techniques assuming that the literature comparisons represent the typical measurement state of the art.

Of course, the obvious question now is "how do these numbers compare with the theory". By nature, this collection of measurement results is not well controlled and should not be taken as a rigorous test of the theory, but rather a check of whether typical measurement results agree with theory. With this in mind, the prediction for Avg DGD / PMD_{EC} is 1, which is well within the 95% confidence interval of the measured 0.97. For RMS DGD / PMD_{INT} and RMS DGD / PMD_{FT}, we have the difficulty that the majority of the measurement results we used provided no information with respect to PMD-bandwidth product, so it is not possible to determine which regime the data fall into. However, we would expect the ratio to be somewhere between 0.866 and 1.0. But, the experimental values are somewhat higher than expected, 1.00 and 1.03 for Fourier transform and interferometry.

There are two possible explanations for this. First, this inflated ratio could be due to data being sampled with a low PMD-bandwidth product. As can be seen from Figures 1 – 3, the majority of the data collected had a PMD below 1 ps (the median RMS DGD of the entire data collection is 0.31 ps). This means that even a source bandwidth of a few hundred nm would not be sufficiently wide to have the ratio converge to the 0.866 value and we would expect a value somewhat larger. However, even in light of this, ratios of 1.0 and greater are still unexpected.

Therefore, we suspect a second source for the disagreement. In the analysis of the second moment of the interferogram (or equivalently, the FAFT spectrum) the PMD can be biased toward smaller values (yielding larger RMS DGD / PMD ratios). In the presence of noise, a common practice is to truncate the wings of the of data, this truncation can easily lead to 10 percent errors in a direction which biases the ratios toward larger numbers (closer to 1.0). As evidence of this, we calculate the ratio using one data set in this collection which had been analyzed using a technique not susceptible to this truncation error and found the ratios to be RMS DGD / PMD_{FT} = 0.84 and RMS DGD / PMD_{INT} = 0.87, closer to the theoretical prediction.

III. Verification of Agreement Using Reference Artifacts

Along with theoretical and experimental methods of determining agreement between measurement techniques, a third possibility is the use of a reference artifact with fixed mode-coupling. In order to avoid the environmental variability of a fiber, sometimes artifacts such as concatenations of polarization maintaining fiber or stacks of crystal waveplates are used to simulate mode-coupled fiber (but without the accompanying variability in the mode coupling geometry). Such devices do yield measurement results similar to those seen for real fibers. DGD vs wavelength, Interferograms and Fixed Analyzer spectral responses all resemble those seen from real fibers. The catch is that these fixed mode-coupled artifacts cannot be used to demonstrate agreement between measurement methods. This is due to the fact described earlier that the theoretical agreements between methods are valid only for the average PMD obtained from a set of statistically independent measurements. Since a fixed mode-coupling artifact cannot have its mode coupling geometry changed, multiple measurements on it are not statistically independent. The only means of obtaining statistical averaging in this fixed mode-coupling case is via wavelength averaging. Therefore, the best agreement among measurement methods would come from using very broad wavelength range sources.

IV. Conclusions

By combining the available experimental comparison results, we have found that on average, all four of the studied measurement techniques yield the same PMD value for measurements on mode coupled fiber. Using a 95% confidence interval, the uncertainty on this agreement is between +/- 7 to 9%.

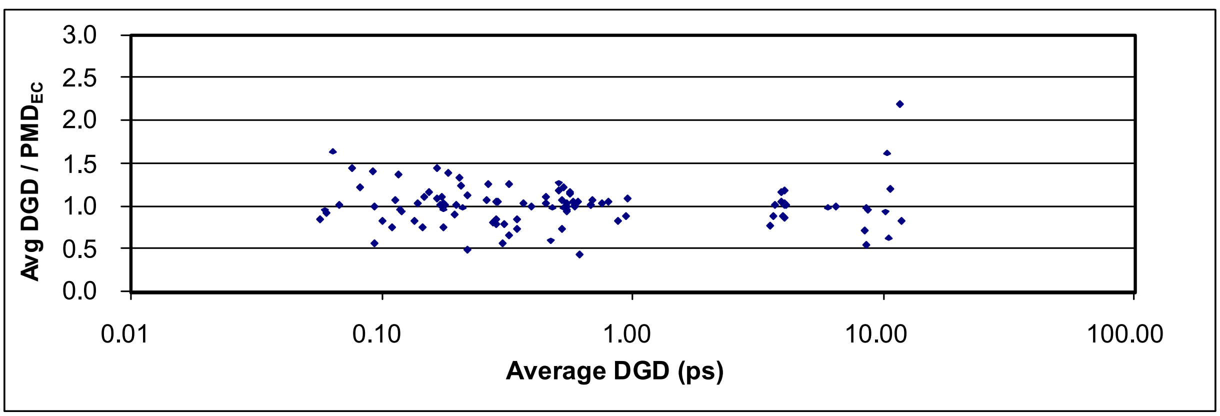

Figure 1. Ratio of JME to FAEC measurements.

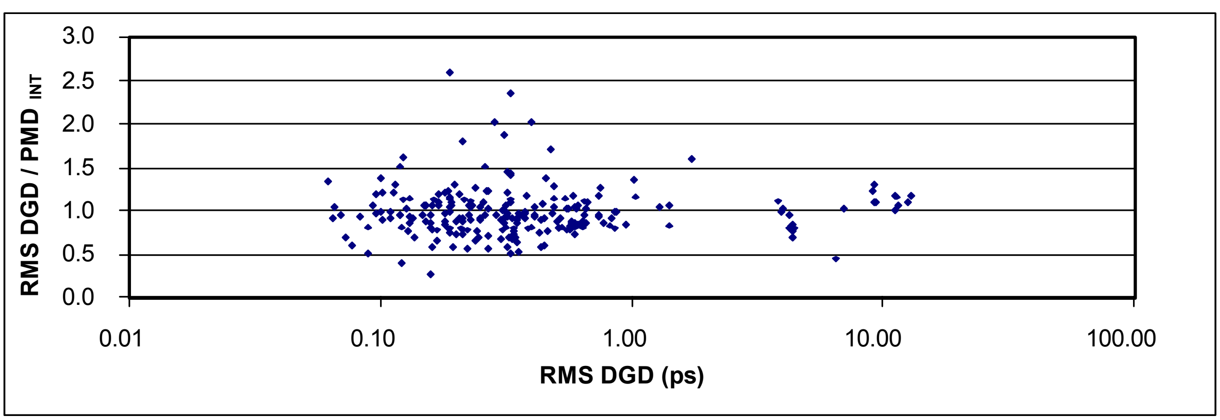

Figure 2. Ratio of JME to INT measurements.

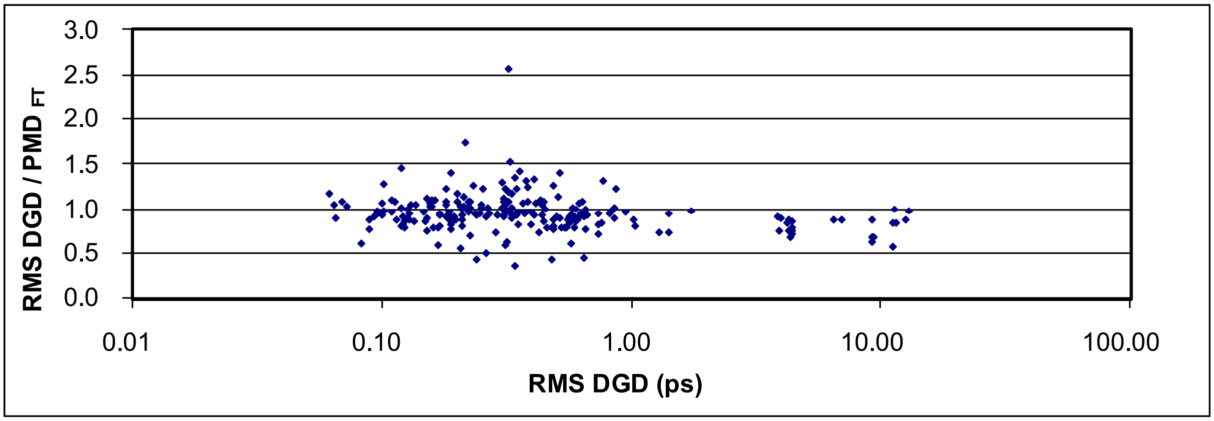

Figure 3. Ratio of JME to FAFT measurements.

[1] Fiber Optic Test Procedure (FOTP) 122, Telecommunications Industry Association.
[2] Fiber Optic Test Procedure (FOTP) 113, Telecommunications Industry Association.
[3] Fiber Optic Test Procedure (FOTP) 124, Telecommunications Industry Association.
[4] C.D. Poole and D.L Favin, "Polarization-mode dispersion measurements based on transmission spectra through a polarizer," J. Lightwave Technol. Vol.12, pp. 917-929 (1994).
[5] B.L. Heffner, "Single-mode propagation of mutual temporal coherence: equivalence of time and frequency measurements of polarization-mode-dispersion," Optics Letters, Vol.19, pp.1104-1106, (1994).
[6] B.L. Heffner, "Influence of optical source characteristics on the measurement of polarization-mode dispersion of highly mode-coupled fibers," Optics Letters, Vol. 21, pp. 113-115, (1996).
[7] M. Artiglia, P. Morra, and C. Sartori, "Polarisation mode dispersion in terrestrial istalled cables: comparison of measurement methods," Proc. Optical Fiber Measurement Conference, Liege, p. II.6, (1995).
[8] N. Gisin, R. Passy, J.C. Bishoff, and B. Perny, "Experimental investigations of the statistical properties of polarization mode dispersion in single mode fibers," Photonics Technology Letters, Vol. 5, pp. 819-821, (1993).
[9] N. Gisin, R. Passy, B. Perny, A. Galtarossa, C. Someda, F. Bergamin, M. Schiano, F. Matera, "Experimental comparison between two different methods for measuring polarisation mode dispersion in singlemode fibres," Electronics Letters, Vol. 27, pp. 2292-2293, (1991).
[10] Y. Namihira, K. Nakajima, and T. Kawazawa, "Comparison of various polarization mode dispersion measurement methods in 1600 km optical amplifier system," Proc. 5th Optoelectronics Conference, Chiba, (1994).
[11] Y. Namihira, K. Nakajima, and T. Kawazawa, "Fully automated interferometric PMD measurements for active EDFAs, fiber optic devices and optical fibers," Proc. Optical Fiber Measurements Conference, Torino, pp. 189-192, (1993).
[12] Y. Namihira, T. Kawazawa, and N. Norimatsu, "PMD reduction of optical fiber cables for transoceanic optical amplifier submarine cable systems," Proc. 42nd International Wire and Cable Symposium, St. Louis, pp. 655-664, (1993).
[13] Y. Namihira, and J. Maeda, "Polarization mode dispersion measurements in optical fibers," Proc. Symposium on Optical Fiber Measurements, Boulder, pp.145-150, (1992).
[14] B. Perny, C. Zimmer, F. Prieto, and N. Gisin, "Polarisation mode dispersion: Large scale comparison of Jones matrix eigenanalysis against interferometric measurement techniques," Electronics Letters, Vol. 32, pp.680-681.
[15] P.A. Williams and P.R. Hernday, "Anomalous relation between ttime and frequency domain PMD measurements," Proc. Optical Fiber Measurement Conference, Liege, p. I.2, (1995).
[16] N. Gisin, B. Gisin, J.P. Von der Weid, and R. Passy, "How accurately can one measure a statistical quantity like polarization mode dispersion?" Proc. Symposium on Optical Fiber Measurements, Boulder, pp.131-134, (1996).
[17] R. DerSimonian and N. Laird, "Meta-analysis in clinical trials", Controlled Clinical Trials, Vol. 7, pp.177-188, (1986).